

Water Vapor Transport and Gas Flow Properties of Textiles, Polymer Membranes, and Fabric Laminates

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INTRODUCTION

VAPOR TRANSFER THROUGH clothing systems may occur due to diffusion (driven by vapor concentration gradients), and convection (driven by air pressure differences). Convective heat and mass transfer in porous media such as textiles is often more important than transport due to diffusion, especially if such materials are used in conditions where a large pressure gradient is present. Laboratory test methods for textiles usually concentrate on one transport mechanism, to the exclusion of the others. Diffusion test methods are particularly easy to perform, and often become the primary ranking and evaluation method for determining the transport properties of textiles. Such test methods can be very misleading for textiles, particularly those which have high air permeability, because a very small pressure gradient can produce large convective flows through the porous structure, far outweighing any diffusive transport that takes place.

The usual procedure is to determine any water vapor diffusion properties and the air permeability properties separately. For textiles, water vapor diffusion test methods include the ASTM Test Method for Water Vapor Transmission of Materials (E 96), and the ISO Test Method for Measurement of Thermal and Water Vapour Resistance under Steady-State Conditions (ISO 11092). Air permeability properties may be determined by a

textile test method, ASTM D737-75—Standard Test Method for Air Permeability of Textile Fabrics. This method, however, is quite limited in that it is more useful for quality-control testing due to its prescription for testing at a single pressure differential (124.5 Pa). A more accurate test method is ASTM F778-88—Standard Methods for Gas Flow Resistance of Filtration Media.

All the methods mentioned above are time-consuming, require large amounts of material, and are not capable of a very wide range of test conditions. They also require two separate kinds of tests to be run to characterize the potential of a given material to transport water vapor through its structure: a water vapor diffusion test and an air permeability test. It would be very appealing to have a test method available that can determine the diffusion and convection properties from the same test, and to be able to directly compare the results obtained between materials as different as air-impermeable membrane laminates, very air-permeable knitted fabrics, woven fabrics, and complicated nonwoven and polymeric foam structures. It would also be appealing to have this test method able to measure these properties for the very small quantities typical of material development programs, where the largest sample available may only be 1–10 cm² in area.

The method described here, based on the Dynamic Moisture Permeation Cell (DMPC) [1,2], satisfies the need for a quick, automated method that can test the mass transport properties of very small pieces of woven and nonwoven fabrics, membranes, and foams. The apparatus is more convenient to use than the traditional test methods for textiles and clothing materials, and allows one to use a wider variety of test conditions to investigate the concentration-dependent and nonlinear transport behavior of many of the semipermeable membrane laminates which are now available. Results generated with the DMPC have been shown to agree with the standard ISO (International Standards Organization) and ASTM (American Society for Testing and Materials) methods for steady-state testing [3]. This paper will review the use of the DMPC to determine the importance of the effects listed below.

Combined Convection/Diffusion

The ability to test under a combined pressure gradient and diffusion gradient allows one to examine the interaction of convective and diffusive mass transfer across a porous textile layer. This is particularly important for clothing systems which have significant air permeability, since most thermal and mass transport laboratory test methods evaluate materials under pure diffusion conditions.

Humidity-Dependent Air Permeability

Fabrics which absorb water vapor from the atmosphere (such as cotton or wool, and to a lesser extent, nylon) experience fiber swelling which tends to close off the pores in the fabric and increase the resistance to convective flow through the material. Changes in fabric air permeability as a function of relative humidity are important for applications involving chemical protective clothing, since these changes will influence the transport of chemical agents in vapor or aerosol form. Test results generated with this apparatus show that it is easy to find fabrics which double their resistance to convective flow due simply to changes in relative humidity.

Concentration-Dependent Permeability

Materials such as Gore-Tex or Sympatex change their transport properties based on the amount of water contained in the hydrophilic polymer layer. The magnitude of the changes in water vapor diffusion resistance as a function of water content are quite large for several common clothing materials and systems.

Temperature-Dependent Permeability

Many polymer membranes exhibit much higher diffusion resistance at low temperatures, which is particularly important for cold weather clothing systems that incorporate materials such as Gore-Tex. Data obtained with this device for several membrane laminates over the temperature range of -5°C to 40°C show that there are significant differences in the way low temperatures affect the diffusion behavior of common laminated membranes.

Transient Sorption/Desorption

The ability of the DMPC to obtain transient equilibration data under step changes of relative humidity is useful for determining time-dependent transport behavior. In these transient situations, temperature changes of as much as 10°C to 20°C can occur, and the variable properties of the material become very important, along with factors such as the sorption rate at which a fiber takes up or releases water vapor to the environment, and the coupling of the differential equations describing the transport of energy and mass through the material.

EXPERIMENTAL METHOD

A schematic of the DMPC test arrangement is shown in Figure 1.

Nitrogen streams consisting of a mixture of dry nitrogen and water-saturated nitrogen are passed over the top and bottom surfaces of the sample. The relative humidity of these streams is varied by controlling the proportion of the saturated and the dry components. By knowing the temperature and water vapor concentration of the entering nitrogen flows, and by measuring the temperature, water vapor concentration, and flow rates of the nitrogen flows leaving the cell, one may measure the fluxes of gas and water vapor transported through the test sample.

With no pressure difference across the sample, transport of water vapor proceeds by pure diffusion, driven by vapor concentration differences. If a pressure difference across the sample is present, transport of vapor and gas includes convective transport, where the gas flow through the sample carries water vapor with it, which may add to or subtract from the diffusive flux, depending on the direction of the convective gas flow. The use of the DMPC to determine water vapor diffusion properties under the condition of no convective flow will be reviewed first as background to describing the use of the DMPC for combined convection/diffusion testing.

Review of Water Vapor Diffusion Test Method

The use of the DMPC for determining water vapor diffusion properties will be reviewed first, followed by a description of the diffusion/convection test method. The following equations for calculating water vapor flux apply to either the top or bottom flows in the cell. Strictly speaking, only one measurement on one side of the cell is necessary; the use of two separate humidity transducers for the top and bottom flows allows two measurements of water vapor flux to be made at the same time, using the equations given below for either the top or bottom flow, as appropriate. Further details may be found in References [1-3].

For this type of test, the mass flow rate of water vapor diffusing through the test sample from one side of the cell to the other is given by:

$$\frac{\dot{m}}{A} = \frac{Q(\delta C)}{A} = \frac{Q(C_2 - C_1)}{A} \quad (1)$$

\dot{m} mass flux of water vapor across the sample (kg/s)

A area of test sample (m^2)

Q volumetric flow rate through top or bottom portion of the cell (m^3/s)

$\delta C = C_2 - C_1$, water vapor concentration difference between incoming

must be able to convert from the known values of relative humidity and temperature to water vapor concentration. The vapor pressure of saturated water vapor in air is obtained from an empirical formula (or tables) as a function of temperature, and then converted to concentration using the perfect gas law.

We may express the water vapor transmission rate in terms of the indicated volumetric flow rate at standard conditions, the humidity difference, and the temperature:

$$\frac{\dot{m}}{A} = \frac{\delta\phi Q_s p_s M_w}{RT_s} \quad (2)$$

M_w molecular weight of water vapor (18.015 kg/mole)

Q_s volume flow rate at standard conditions of 0°C and atmospheric pressure (m^3/s)

R universal gas constant (8314.5 N·m/kg·K)

T_s reference temperature at standard conditions of 0°C in degrees K (273.15 K)

p_s saturation vapor pressure of water (Pa)

$\delta\phi = \phi_2 - \phi_1$, relative humidity difference between incoming stream (ϕ_1) and outgoing stream (ϕ_2) in top or bottom portion of the moisture permeation cell

$\phi = p_v/p_s$, relative humidity

p_v vapor pressure of water (Pa)

For the present test apparatus, various sample holders are available that have different test sample measurement areas and different downstream locations from the flow inlet. A typical sample measurement area is $1.0 \times 10^{-3} \text{ m}^2$, and the sample is located equidistant from the inlet and outlet ports of the cell. The typical volumetric flow rate used is $3.33 \times 10^{-5} \text{ m}^3/\text{s}$ (2000 cm^3/min). The dimensions of the DMPC were chosen to assure flow velocities of at least 0.5 m/s over the sample to minimize the contribution of boundary air layer resistances to the test measurements. Details of the sample holder are shown in Figure 2.

The sample sizes are kept quite small to make it possible to evaluate novel membranes and laminates, which are often produced in quantities too small for testing by some of the standard water vapor diffusion test methods. The small sample area makes it necessary to test at different locations across a typical roll of fabric to adequately characterize a given material. Sample mounting methods vary according to the material being tested. Thin materials, such as laminated materials and woven cloth, were originally tested with rubber sealing gaskets to prevent leakage, but the sealing

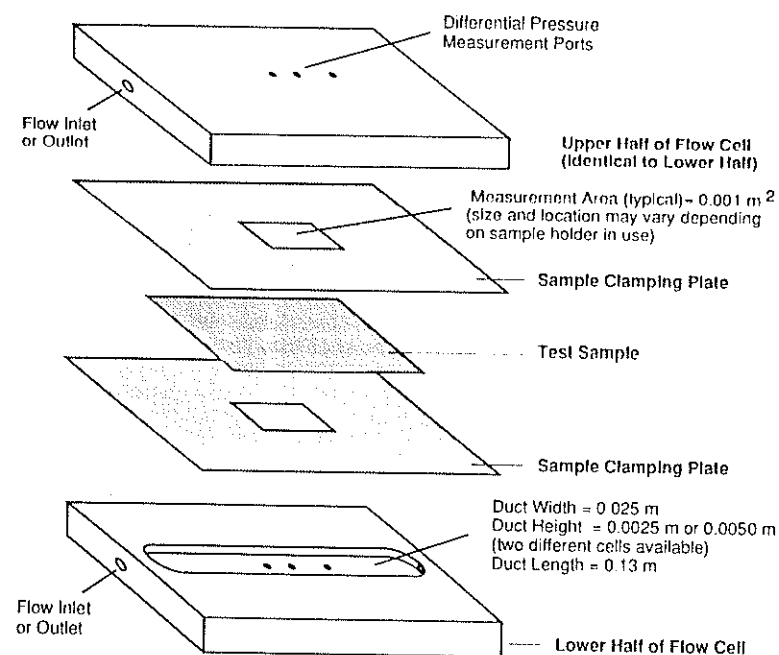


FIGURE 2. Schematic and dimensions of the sample holder for the DMPC.

proved to be unnecessary for most materials; the clamping force provided by the mounting bolts has proven to be sufficient to prevent any leakage. Thick materials that are highly permeable require special sealing methods, such as edge sealing by molten wax, or the use of a curable sealant. The testing of thicker materials also requires a larger sample area to minimize factors such as edge effects.

Diffusion Test Procedure

The actual test is conducted under the control of a personal computer (PC) connected to the flow controllers, automated valves, and the various measurement transducers through input and output boards (see Figure 1). Various options exist within the software for operator input setpoint information, or preset files containing the setpoint information. The computer applies the proper setpoint voltage to each controller to produce the desired relative humidity in the upper and lower gas streams entering the DMPC. The A/D

board in the PC reads analog voltage outputs of the relative humidity, RTD, thermocouples, differential pressure transducer, mass flow meters, etc., records the data on disk, calculates parameters of interest, and plots results to the PC screen. The software applies operator-determined equilibration criteria to determine when equilibration has been reached for that setpoint. Once equilibration is reached, the results (humidity, calculated flux, etc.) may be output to a printer and to a data file on disk. The computer then proceeds to the next setpoint and repeats the process.

The pressure drop across the sample is monitored by means of an MKS Baratron Type 398 differential pressure transducer, with a Type 270B signal conditioner (MKS Instruments, Inc.). For measurement of pure diffusion, especially for materials such as fabrics, which may be quite permeable to convective flows, it is important to make sure that the pressure drop across the sample is zero, so that transport takes place only by pure diffusion. The pressure drop is continuously monitored and displayed, and is controlled by means of two automated valves at the outlets of the cell. For the permeable fabrics, this system also allows one to do testing under controlled conditions of a defined pressure drop across the sample, so that transport takes place by both diffusion and convection (which will be described later). This makes it possible to determine an air permeability value from the apparatus, in addition to the water vapor diffusion properties of the test sample.

Materials which have a constant mass transfer coefficient show a linear slope on plots of flux versus concentration difference across the sample. These materials do not change their transport properties as a function of water content or test conditions.

For materials which do not have a constant slope, the data points for a test series will not superimpose, but will form a set of curves for each test condition. From an evaluation of the flux versus concentration difference curve at various points we can calculate values for the material diffusion resistance, which will be a function of the concentration of water in the material.

We define a total resistance to mass transfer as the simple addition of an intrinsic diffusion resistance due to the sample (R_i) and the diffusion resistance of the boundary air layers (R_{bl}):

$$\frac{\dot{m}}{A} = \frac{\Delta \bar{C}}{(R_i + R_{bl})} \quad (3)$$

$$R_i \left[\frac{\Delta \bar{C}}{\left(\frac{\dot{m}}{A} \right)} \right] - R_{bl} \quad (4)$$

\dot{m} = mass flux of water vapor across the sample (kg/s)

A = area of test sample (m²)

$\Delta \bar{C}$ = log mean concentration difference between top and bottom nitrogen streams (kg/m³)

R_f = intrinsic diffusion resistance of sample (s/m)

R_{bl} = diffusion resistance of boundary air layers (s/m)

The log mean concentration difference across the sample is appropriate since there is a significant change in the concentration of the gas stream both below and above the sample. In addition, the gas streams may not necessarily be in parallel unidirectional (cocurrent) flow, but they may be run in a counter flow to maintain a more constant concentration gradient across the sample. The log mean concentration difference is defined as:

$$\Delta \bar{C} = \frac{\Delta C_a - \Delta C_b}{\ln(\Delta C_a / \Delta C_b)} \quad (5)$$

ΔC_a = concentration difference between the two gas streams at one end of the flow cell (kg/m³)

ΔC_b = concentration difference between the two gas streams at the other end of the cell (kg/m³)

For parallel cocurrent flow, the concentration differences are between the top and bottom incoming flow at one end of the cell (ΔC_a), and the difference between the top and bottom outgoing flows at the other end of the cell (ΔC_b). For countercurrent flow, the concentration differences are between the incoming and outgoing flows at one end of the cell (ΔC_a), and the incoming and outgoing flows at the other end of the cell (ΔC_b).

USE OF DMPC FOR CONVECTION/DIFFUSION STUDIES

The DMPC may also be run with a specified pressure drop across the sample so that transport takes place by both diffusion (driven by concentration differences) and convection (driven by gas phase pressure differences) [7]. The simplest experiment to run is shown in Figure 3. Gas enters the DMPC at a relative humidity of 0.90 (90% r.h.) on the top portion of the cell, and 0.0 (0% r.h.) on the bottom of the cell. The automated valves are used to restrict the flow on one or the other sides of the cell which causes the pressure in one side of the cell to be higher than in the other, causing convective flow across the sample, in addition to the diffusion flux taking

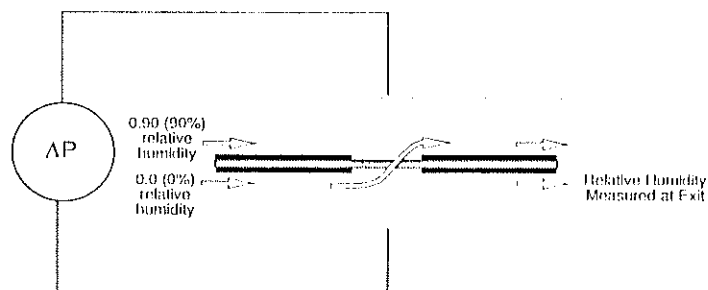


FIGURE 3. Convection/diffusion experiment in the DMPC: example shows bottom outlet flow restricted to force convective flow across sample, which opposes diffusive flux of vapor.

place due to the concentration gradients.

Measurements are taken as a function of pressure drop across the sample, where the convective flow and pressure drop are gradually increased in stepwise increments. In addition to the pressure drop, it is useful to have an actual measurement of gas flow through the sample. An electronic mass flow meter (Model 822 Top-Trak, Sierra Instruments, Inc.) connected to the lower outlet of the cell as shown in Figure 1, is used to record the mass flow rate of gas through the test material.

Typical measurements of water vapor diffusion resistance and mass flow rate as a function of pressure drop are shown in Figures 4 and 5 for three materials: (1) a microporous polytetrafluoroethylene (PTFE) membrane, with low water vapor diffusion resistance, but a high resistance to convective gas flow (low air permeability), (2) a knit polyester fabric with a slightly greater resistance to water vapor diffusion, but very low air flow resistance (high air permeability), (3) a woven nylon fabric with still higher water vapor diffusion resistance, and an air flow resistance intermediate between the other two materials.

Figure 4, which shows flow rate as a function of pressure drop, is directly related to the air permeability of the material. The greater the slope of the line for a given material, the greater the air permeability. Figure 4 shows that the microporous PTFE membrane has a very low air permeability (high flow resistance), the knit polyester fabric has a high air permeability, and the woven nylon fabric is intermediate between the other two materials. Calculation of the air flow resistance from the data in Figure 4 will be discussed later.

Figure 5 shows the apparent water vapor diffusion resistance as a function of pressure drop. This plot illustrates the interaction of convective and diffusive transport. The intersection of each material's curve with the $\Delta P =$

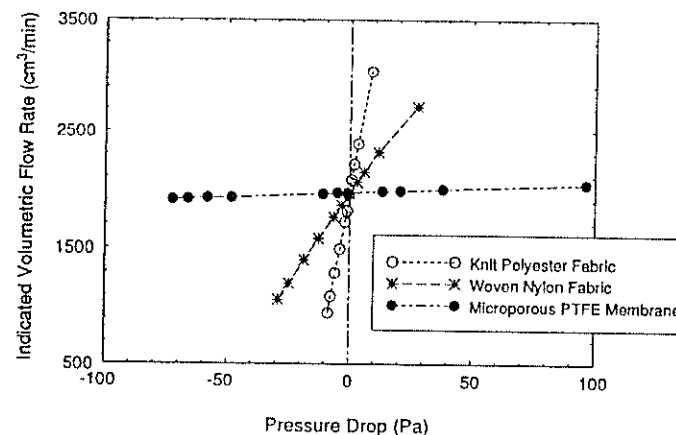


FIGURE 4. Flow rate through fabric as a function of pressure drop.

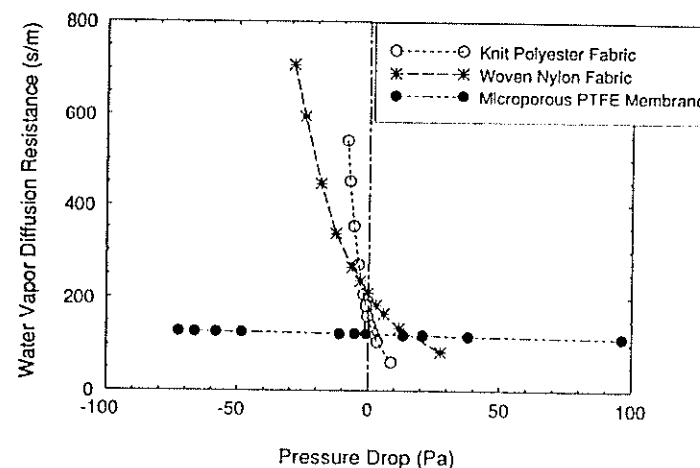


FIGURE 5. Diffusion resistance as a function of pressure drop.

0 point on Figure 4 defines the true water vapor diffusion value for that material, which is illustrated with an expanded scale in Figure 6.

At the condition of 0 pressure drop, the PTFE membrane has the lowest diffusion resistance, followed by the knit polyester, with the nylon fabric having the highest diffusion resistance. This PTFE membrane has previously been shown to have diffusion resistance of about 6-8 s/m [2], which means that the boundary layer resistances in this flow cell (defined by flow rates and flow geometry) are approximately 115 s/m. Thus, the true diffusion resistance of each material is equal to the difference between its total resistance from Figure 6, and the boundary layer resistance. The resulting intrinsic diffusion resistances are 6 s/m for the PTFE membrane, 96 s/m for the nylon fabric, and 36 s/m for the polyester fabric. These values agree well with those obtained previously for these materials [8].

However, since these materials differ greatly in their air permeability properties, the change in apparent diffusion resistance as the pressure drop increases is quite different for the various materials. The PTFE membrane has a nearly constant diffusion resistance, due to its low air permeability. Because of the polyester fabric's high air permeability, even at very low pressure drops (for example at 10 Pa), its apparent diffusion resistance is less than that of the PTFE membrane.

The ability to conduct testing over a range of pressure drops increases the accuracy of the water vapor diffusion value. It is clear that slight variations

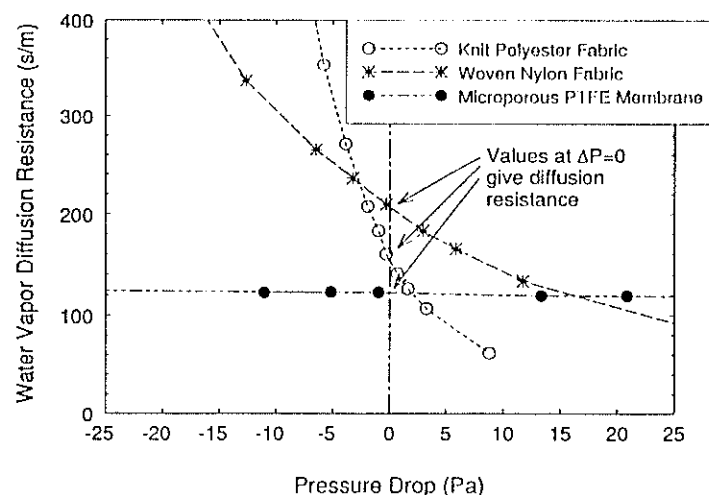


FIGURE 6. Use of diffusion/convection data to define true diffusion resistance.

in pressure drop across a sample with high air permeability will greatly influence the measured water vapor diffusion resistance. Diffusion test methods which do not control or monitor the convective flow through the sample are prone to measurement and ranking errors caused by air flow through the sample.

The characteristic curve shown in Figure 6, which illustrates the interaction between diffusive and convective transport, is more realistic in terms of the transport processes taking place in clothing systems, where both modes of transport take place at the same time. Water vapor diffusion properties alone, which may rank materials such as the PTFE membrane as superior to more air-permeable materials, can be very misleading when ranking candidate materials for comfortable or breathable clothing systems.

Calculating Air Flow Resistance

There are many definitions of the permeability or the flow resistance; most often the permeability is given by Darcy's Law [9] such that:

$$v = \frac{-k_D}{\mu} \frac{\Delta p}{\Delta x} \quad (6)$$

v = apparent gas flow velocity (m/s)

k_D = permeability constant (m^2)

μ = gas viscosity (17.85×10^{-6} kg/m·s for N_2 at $20^\circ C$)

Δp = pressure drop across sample (N/m^2 or Pa)

Δx = thickness (m)

For low velocity flows, where the apparent Reynolds number (based on nominal particle diameter or pore sizes) is much less than 10, a plot of pressure drop versus volumetric flow rate or velocity will give a constant value for the permeability constant k_D . At higher flow rates, where inertial effects begin to compete with viscous flow effects, pressure drop-flow rate plots will begin to deviate from linearity, and inertial effects need to be considered. Previous work on air penetration through clothing systems has shown that air pressure differences across textile layers, due to factors such as wind or body movement, are usually less than 100 Pa [10-13]. For the testing presented in this report, flow rates and pressure drops are low enough so that inertial effects are not readily apparent in the experimental results.

The DMPC operated in the diffusion/convection mode provides plots of pressure drop versus either mass flow rate or volumetric flow rate, seen previously in Figure 4. Volumetric flow rate is the most convenient to use, so the permeability constant may be found from:

$$k_D = \left(\frac{\mu Q}{A} \right) \left(\frac{\Delta x}{\Delta p} \right) \quad (7)$$

μ = gas viscosity (17.84×10^{-6} kg/m·s for N_2 at 20°C)

Q = total volumetric flow rate (m^3/s)

A = apparent sample flow area (1.0×10^{-3} m^2 for DMPC sample holder)

Δx = thickness (m)

Δp = pressure drop across sample (N/m^2 or Pa)

Although thickness measurements for textiles seem simple, they are often problematic, and can be a large source of error if they are incorporated into reported measurements of Darcy permeability. It is preferable to present the pressure-drop/flow rate results in terms of an apparent flow resistance defined as:

$$R_D = \left(\frac{A \Delta p}{\mu Q_{\text{total}}} \right) \quad (8)$$

R_D = apparent Darcy flow resistance (m^{-1})

The volumetric flow rate shown in Figure 4, measured by the electronic mass flow meter, is the equivalent volumetric flow rate at the reference temperature (T_0) of 0°C (273.15 K), and reference atmospheric pressure (p_0) of 1.01325×10^5 Pa. The actual volumetric flow rate at a given temperature may be found from the mass flow rate indicated by the electronic mass flow meter (Q_0), the ambient temperature (T_a), and the ambient pressure of the actual flow (p_a). The pressure correction is negligible ($p_0/p_a \approx 1$), so only the temperature correction needs to be made. The correction to obtain the actual volumetric flow rate (Q_{total}) from the indicated mass flow rate (Q_0) is:

$$Q_{\text{total}} = Q_0 (T_a / T_0) (p_0 / p_a) \approx Q_0 (T_a / T_0) \quad (9)$$

Note that the quantity $(\Delta p / Q_{\text{total}})$ is equal to the inverse of the slopes of the curves shown in Figure 4 (after correcting to the proper temperature as shown above). Figure 4 may be replotted as shown below in Figure 7.

Thus the air flow resistance can be found from the slope of each curve in Figure 7, using the known flow area and gas viscosity according to Equation (8). For the three materials shown in Figure 7, the equivalent air flow resistance is 2.78×10^7 m^{-1} for the polyester fabric, 1.14×10^8 m^{-1} for the

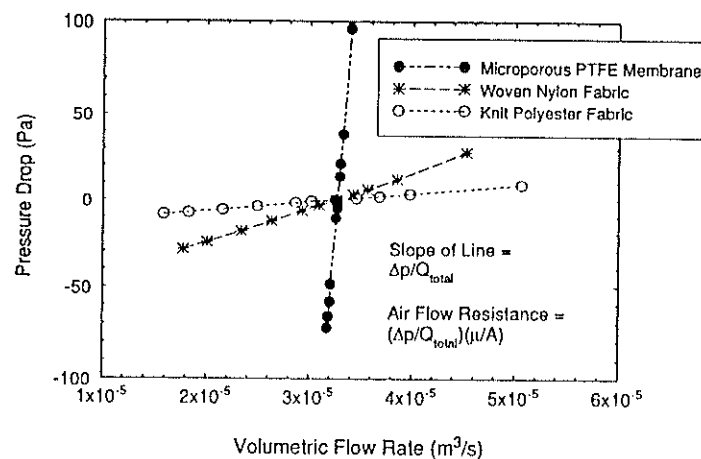


FIGURE 7. Pressure drop across sample as function of flow rate.

nylon fabric, and 4.25×10^9 m^{-1} for the PTFE microporous membrane. These values agree with those obtained previously for these materials by another method [14].

If the material thickness is known, the Darcy permeability (usually reported in units of m^2) can be found from the apparent flow resistance as:

$$k_D = \frac{\Delta x}{R_D} \quad (10)$$

The convection/diffusion test method is most appropriate for air permeable materials, such as porous textiles, membranes, or foams. It can be used for air-impermeable materials, which is useful to show the relative importance of convective flow versus diffusive flow. The convection/diffusion test method is quite convenient for screening a large number of samples—particularly developmental materials—since it gives an air permeability and a water vapor diffusion value from a single test.

However, for materials such as semipermeable membrane laminates, or porous textiles that have humidity-dependent air permeability, the single air flow resistance and single diffusion resistance number obtained from a convection/diffusion test can be misleading, and it would be preferable to perform a separate diffusion test, and a separate air permeability test to separate out these two effects. Both of these complicating factors are discussed in the next two sections.

USE OF DMPC FOR CONCENTRATION-DEPENDENT DIFFUSION IN MEMBRANE LAMINATES

Vapor transport across nonporous hygroscopic polymer membranes and films is often highly dependent on the amount of water present in the polymer. Many commercially available semipermeable membrane laminates such as Gore-Tex and Sympatex exhibit this concentration-dependent behavior to varying degrees. The DMPC, when operated in the pure vapor diffusion mode (no pressure drop across the sample) is capable of showing this concentration-dependent transport behavior [1-5,7,8]. For samples which are air-impermeable, convection/diffusion testing does not provide any extra information, and it is better practice to conduct pure diffusion testing that evaluates water vapor transport under a variety of environmental conditions corresponding to different levels of water content in the hygroscopic polymer membrane or membrane laminate. This concentration-dependent behavior is illustrated below in Figure 8. Two semipermeable membrane laminates (Gore-Tex and Sympatex) are shown which exhibit concentration-dependent transport behavior. They may be compared to the microporous PTFE membrane, also shown in Figure 8, which does not show the same type of concentration dependence. Further information is available in References [1-5] and [7,8].

If one were to blindly apply the convection/diffusion test method to

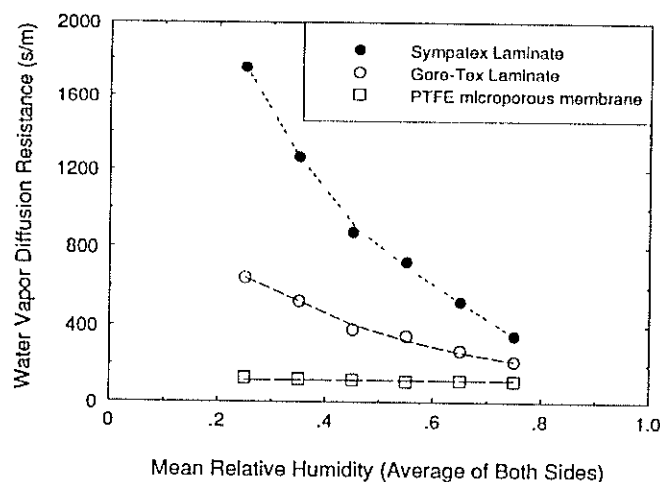


FIGURE 8. Concentration-dependent water vapor transport behavior of two semipermeable membrane laminates.

these kinds of materials, one would obtain a diffusion resistance that is only representative of one mean relative humidity, which would not capture the true variability of the transport behavior of these particular materials.

USE OF DMPC FOR HUMIDITY-DEPENDENT AIR PERMEABILITY

The convection/diffusion test method results in a single number for the air flow resistance of a porous material. Porous hygroscopic materials often exhibit humidity-dependent air permeability due to the swelling of the solid matrix as it takes up water vapor from the environment. These effects are most evident in materials such as tightly-woven fabrics, low porosity hygroscopic membranes, and nonwoven fiber mats.

For a material such as this, the DMPC can be used to conduct a more traditional air flow resistance test as a function of relative humidity [14,15]. The humidity-dependent air flow resistance curves for a variety of air-permeable fabrics is shown in Figure 9.

It is possible to account for the nonlinearity of the convection/diffusion test due to this humidity dependence, as detailed in Reference [16], but it is usually simpler to perform this separate air flow resistance test to produce plots similar to that shown in Figure 9.

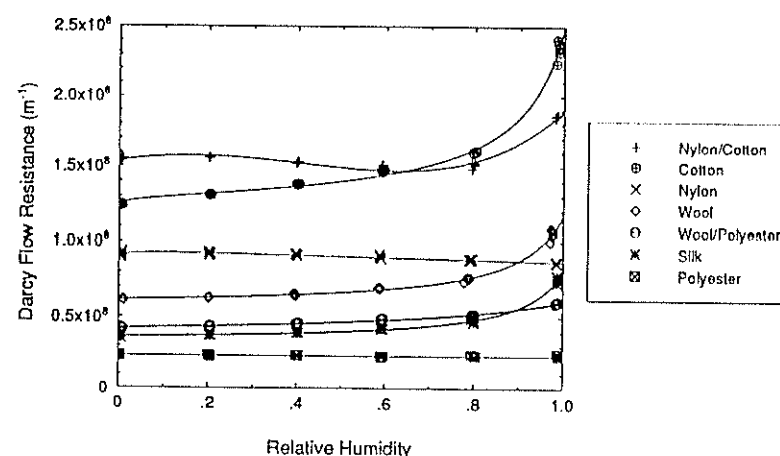


FIGURE 9. Humidity-dependent air flow resistance of seven fabrics [14,15].

USE OF DMPC FOR TEMPERATURE-DEPENDENT DIFFUSION IN MEMBRANE LAMINATES

Osczevski [17] has shown that water vapor diffusion in hydrophilic films and membranes can be affected by the ambient temperature. The water vapor diffusion resistance increases at lower temperatures, which lowers the rate at which water vapor is transported across the layer. This effect could be important for the ability of cold weather clothing to dissipate water vapor during active wear, or for the ability of boots, gloves, and sleeping bags to dry out under cold conditions.

It is difficult to evaluate this effect with other common textile test methods. The DMPC is ideally suited for this type of study, due to its complete control over the humidity on the two sides of the test sample, and the ability to control the temperature of the test system. The humidification system based on the water bubblers is adequate for temperatures from 0°C (ice/water mixture) to 40°C. For subzero temperatures, the bubblers must be replaced by flow tubes filled with ice chips. A flow path long enough for the gas to become saturated with respect to the vapor pressure of water vapor over ice at the particular test temperature is necessary for the subzero tests.

An example of the temperature-dependent water vapor diffusion behavior of four membrane-based materials is shown in Figure 11. Results are shown for the mean relative humidity condition of 0.40 (40%) (average of 0.80 on one side and 0.0 on the other).

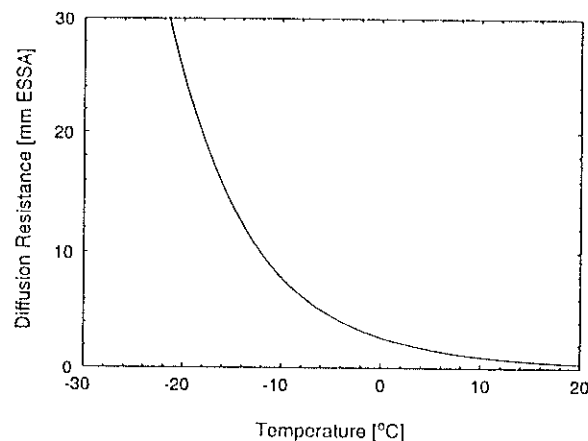


FIGURE 10. Change in water vapor diffusion resistance of a hydrophilic membrane, redrawn from Osczevski [17].

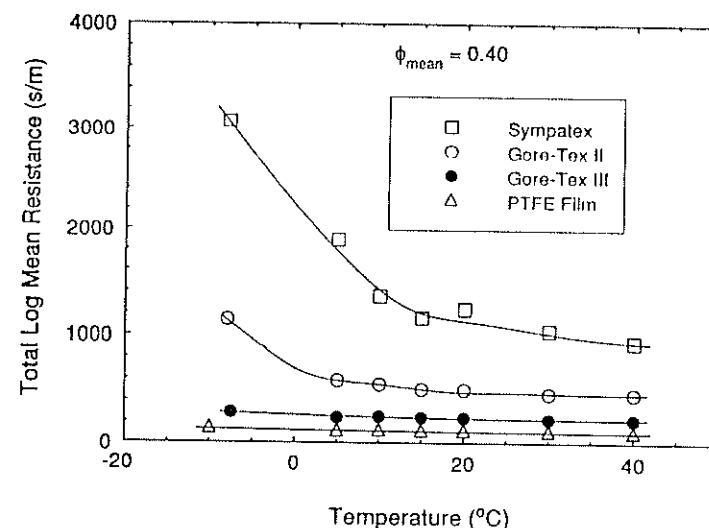


FIGURE 11. Temperature dependence of water vapor diffusion resistance for four membrane-type materials (two hygroscopic, two nonhygroscopic).

Results for other mean relative humidity conditions showed that the temperature effects on the measured diffusion resistance are much greater when the hydrophilic polymer contained less sorbed water. At the higher mean relative humidity test conditions, the properties varied less with temperature.

The method used by Osczevski was a modified cup method, and could not independently control the humidity on the two sides of the sample [17], so the temperature-dependent results also varied in the mean relative humidity to which the sample was exposed. The DMPC's complete control over temperature, humidity, and flow rates allows the temperature-dependent effects to be separated from these concentration-dependent effects. In effect, the DMPC allows the experimenter to explore the temperature dependence of the diffusion behavior at different points on the isotherm of the hydrophilic polymer component of a polymer film or membrane laminate [18,19].

USE OF DMPC FOR TRANSIENT DIFFUSION STUDIES

The automated DMPC apparatus can be used to conduct testing of materials under non-steady-state conditions, such as a change in relative humidity, temperature, or pressure difference across the sample. In these

transient situations, the variable properties of the material become very important, along with factors such as the sorption rate at which a fiber takes up or releases water vapor to the atmosphere.

A group of porous textile materials that have a range of properties are selected to illustrate the use of the DMPC for characterizing transient diffusion properties. Further information on these fabrics, and the results, may be found in Reference [8].

We first illustrate the use of the DMPC to obtain transient results for fabrics subjected to step changes in relative humidity. In these experiments, thermocouples are sandwiched between two layers of fabric, to record temperature changes as the fabric absorbs or desorbs water vapor from the gas stream flowing on the two sides of the DMPC. Three thermocouples are used as shown in Figure 12. Thermocouple diameter was 1.27×10^{-4} m (0.005 in), with a response time listed by the manufacturer as 0.04 s in water and 1 s in still air. Smaller thermocouples with a diameter of 2.54×10^{-5} m (0.001 in) were used initially, but proved to be quite fragile and easily damaged. The temperature changes recorded with both sizes of thermocouple were identical, so that errors due to conduction and the heat capacity of the thermocouple wire are minimal.

Nine setpoints were used to examine time-dependent diffusion in these

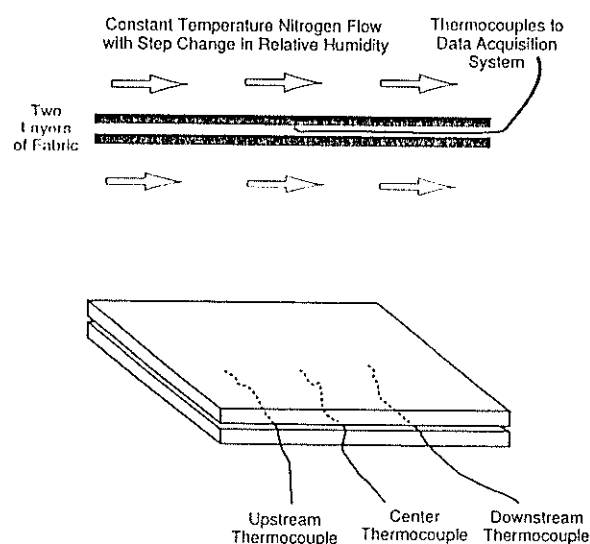


FIGURE 12. Instrumented test fabric in DMPC to record temperature changes of hygroscopic fabrics.

hygroscopic porous textile layers, as given in Table 1. In this series of setpoints, the pressure drop across the sample is set to zero, so that there is no convective flow across the sample, and transport takes place only by diffusion driven by concentration differences.

The first three setpoints are used to look at the situation when a completely dry fabric, equilibrated at 0% relative humidity, is suddenly exposed to a relative humidity of 100% on the two sides of the fabric facing the gas flows on the top and bottom of the DMPC. For hygroscopic fabrics, the textile fibers will absorb water vapor from the gas flow, and release the heat of sorption, which results in a rise in temperature of the fabric, as recorded by the three thermocouples. When the relative humidity is suddenly changed back to 0%, the water is desorbed from the textile fibers, and the temperature drops, due to the change of phase of the water as it leaves its sorbed state in the textile fiber and vaporizes. The rate at which the temperature rises and falls is related to the mass transport and thermal transport properties of the textile material, and the gas flows, and serves as a convenient experimental verification of numerical predictions of transient behavior [8].

The next six setpoints are a sequence of humidity gradients across the sample, where there is a net flux of water vapor from one side of the cell to another. Setpoint #4, where the relative humidity is suddenly changed from 0% to 60%, provides another set of experimental results that are particularly convenient for verifying numerical predictions because both temperature measurements and the measurement of relative humidity of the gas flow as a function of time are available.

An example of the full sequence of nine setpoints, for the cotton fabric, shown as a function of time, is given in Figure 13. For clarity, only one thermocouple record is shown in Figure 13.

Table 1. Nine setpoints for transient diffusion tests.

Setpoint	Relative Humidity for Top Gas Flow	Relative Humidity for Bottom Gas Flow
1	0.0	0.0
2	1.0	1.0
3	0.0	0.0
4	0.6	0.0
5	0.8	0.0
6	1.0	0.0
7	1.0	0.2
8	1.0	0.4
9	1.0	0.6

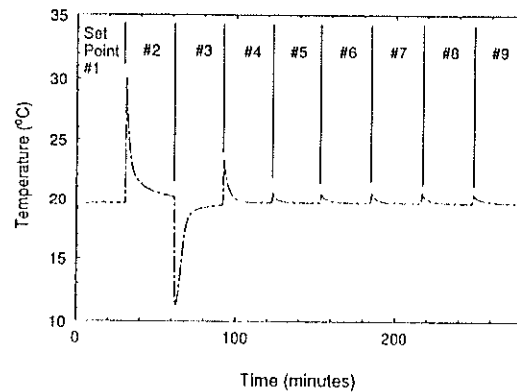


FIGURE 13. Temperature changes of two layers of cotton fabric subjected to step changes in relative humidity, at a constant gas flow temperature of 20°C.

The large temperature changes due to sorption/desorption are particularly evident for setpoints #2 and #3.

The shape of these transient temperature curves are a complex function of the velocity of the gas flows on the two sides of the fabric samples, which influences the external heat and mass transfer coefficients and the thermal and mass transport properties of the textile layers. An example of the temperature transients for all seven test fabrics, for setpoint #2 (step change for 0.0 to 1.0 relative humidity), is shown in Figure 14. Here only the first four minutes are shown, to make it easier to distinguish the response of the different materials shown. The peak temperatures for each of the materials is also shown on the plot.

Figure 14 can be misleading, in that it shows a single well-defined experimental temperature transient for each material. Since there are concentration and temperature gradients down the length of the test sample, due to the influence of the developing thermal and concentration boundary layers, the temperatures of the upstream, center, and downstream thermocouples (refer to Figure 12) are slightly different, as shown in Figure 15.

Experimental results such as these can be compared with the results of a numerical code that solves the partial differential equations describing the coupled diffusion of heat and mass through hygroscopic porous textiles [20,21]. An example of the comparison of the experimental and the numerical results is shown in Figure 16.

Another transient measurement that is useful for verifying numerical predictions of transient diffusion behavior is the experimental measure-

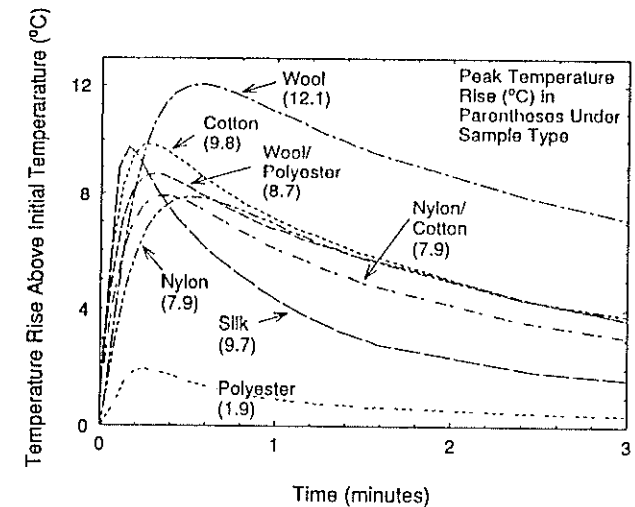


FIGURE 14. Temperature changes due to water vapor sorption for seven fabrics during step changes in relative humidity from 0.0 to 1.0.

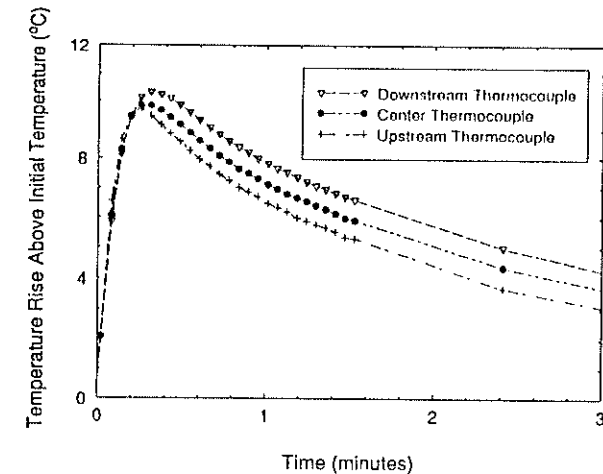


FIGURE 15. Temperature changes for the three thermocouples, for the cotton fabric, due to water vapor sorption during step changes in relative humidity from 0.0 to 1.0.

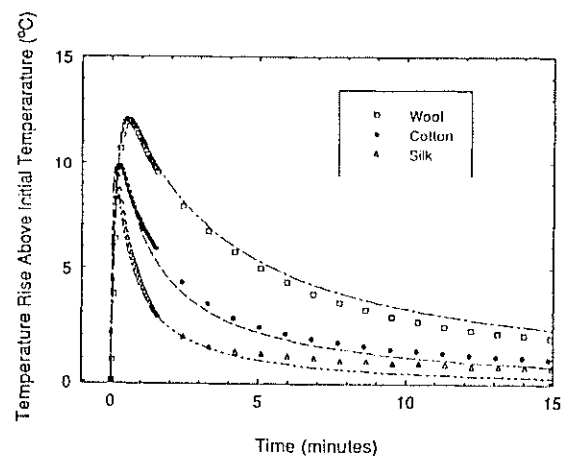


FIGURE 16. Comparison of numerical predictions to experimental results of centerline temperature of wool, cotton, and silk fabrics subjected to step changes in relative humidity [20].

ment of the water vapor concentration change on one side of the fabric as the relative humidity on the other side of the fabric is changed. Setpoint #4 is useful for this purpose, since there is a step change from 0% relative humidity on both sides of the sample, to 60% relative humidity on one side. Following this step change in relative humidity, the rate of change of

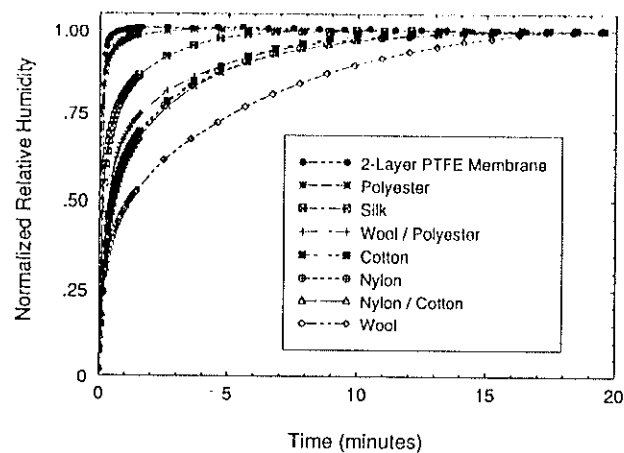


FIGURE 17. Relative humidity normalized by final equilibrium value, during step change from 0.0 to 0.6, at constant temperature of 20°C.

the measured relative humidity on the "dry side" of the cell is greatly affected by the sorption kinetics of a hygroscopic material. Figure 17 shows the change in relative humidity on the bottom side of the DMPC when the humidity on the top side is suddenly changed to 0.6. Figure 17 has had the relative humidity normalized by the final equilibrium relative humidity for setpoint #4. Also shown in this plot is the value for two layers of the PTFE membrane, which is completely nonhygroscopic; it serves to indicate the response time of the relative humidity sensors to a step change.

CONCLUSIONS

The dynamic moisture permeation cell permits rapid testing of small quantities of permeable fabrics and semipermeable laminates under a wide variety of test conditions, which allows determination of a material's transport behavior under test conditions that are difficult or impossible to reach using existing standard laboratory test methods.

Water vapor permeation results obtained with the DMPC are in excellent agreement with those from the ISO 11092 sweating guarded hot plate test method, and from a modified inverted ASTM E 96 cup test [3].

The DMPC is particularly useful for characterizing transient diffusion of hygroscopic fabrics subjected to step changes in relative humidity. It provides excellent control over temperatures, pressures, and vapor concentrations, which is necessary for accurately determining the time-dependent, concentration-dependent, temperature-dependent, and nonlinear transport properties of clothing materials.

When operated as an automated air permeability apparatus, the DMPC provides experimental data on convective gas flow transport properties; e.g., Darcy permeability or Darcy flow resistance. It provides a means of exploring and characterizing the way in which fabric structural changes, caused by fiber swelling at high humidities, can drastically change the air permeability of fabrics incorporated into clothing systems.

The DMPC also provides a controlled means of testing porous fabrics under conditions of combined diffusion and convective transport. This testing is useful for determining the gas flow resistance property (air permeability) and water vapor diffusion resistance property (water vapor transmission rate), from a single experimental run. This eliminates the need for two separate tests, which is the usual procedure.

The convection/diffusion test method is ideal for rapid screening and comparison of the properties of a large number of materials. Because the required test sample size is much less than that required for most other standard types of air permeability and water vapor diffusion test methods,

the convection/diffusion test method is particularly well-suited for material development efforts aimed at developing porous woven and nonwoven textiles, coating processes for porous substrates, polymeric foams, microporous polymer membranes and laminates, and novel electrospun nonwoven fiber mats [22–24].

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